Jet Propulsion Laboratory
California Institute of Technology

Design, Modeling and Testing of a O2/CH4 Igniter for a Hybrid Rocket Motor

Thursday 26th July 2017

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Agenda

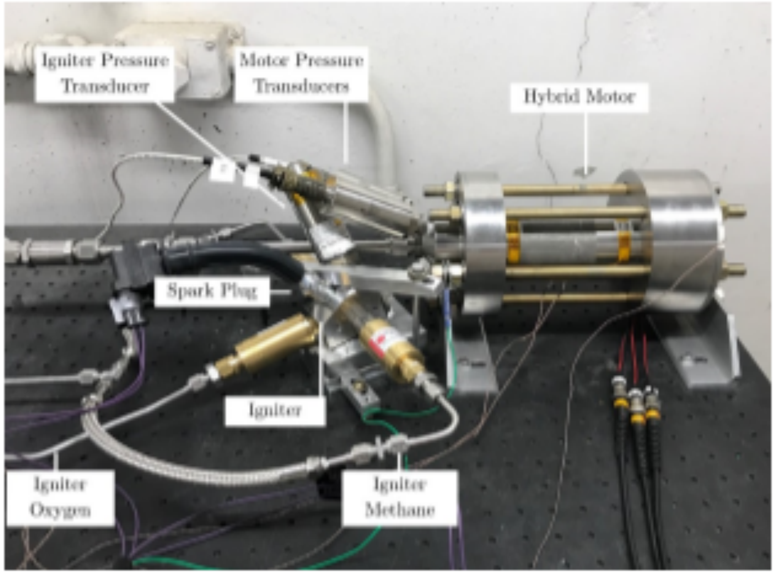
- Introduction
- Igniter Design
- Mass Flow Calibration Tests
- Igniter Tests
- Conclusion

Introduction (1)

- Hybrid rocket motors represent a promising alternative to conventional chemical propulsion systems due to their high performance and increased safety
- A hybrid propulsion test facility has been built at NASA's Jet Propulsion Laboratory
- Approximately 50 tests have been completed showing the feasibility of a hybrid propulsion system for an interplanetary CubeSat/SmallSat
- A gaseous oxygen/gaseous methane system is being considered for use as a re-usable hybrid rocket motor igniter on a SmallSat application
- Preliminary tests of the igniter system have been completed successfully, and ongoing work is being undertaken in an attempt to improve the igniter design
- The basic system includes an igniter combustion chamber where ignition of the O2/CH4 mixture is initiated by a commercial spark plug

Introduction (2)

- Solid PMMA and gaseous O2 are currently being used as the fuel and oxidizer, respectively, for the main hybrid motor
- An igniter test program and modeling effort are currently ongoing to enable multiple starts as would be required for interplanetary missions
- Limited experimental data is available at high pressures and with pure oxygen, which is where this system is designed to operate
- This lack of pre-existing relevant data has motivated an internal test campaign



Introduction (3)

- Key Design Requirements:
  - *Reliability*
  - *Main motor successful ignition*
  - *Repeatable ignition delay time*
  - *Low power requirements*
  - *Low gas volume of fuel/oxidizers*
  - *System simplicity*
- The igniter is designed to operate using regulated O2 that will also supply the hybrid motor
- The methane for this flight design concept would be provided from a stand-alone tank, with limited or no regulation
- An important long-term goal is to determine a reasonable range of operating oxidizer to fuel ratios for the igniter. This range of O/F can be used to determine the required methane tank pressure and size in order to complete a given number of hybrid motor restarts

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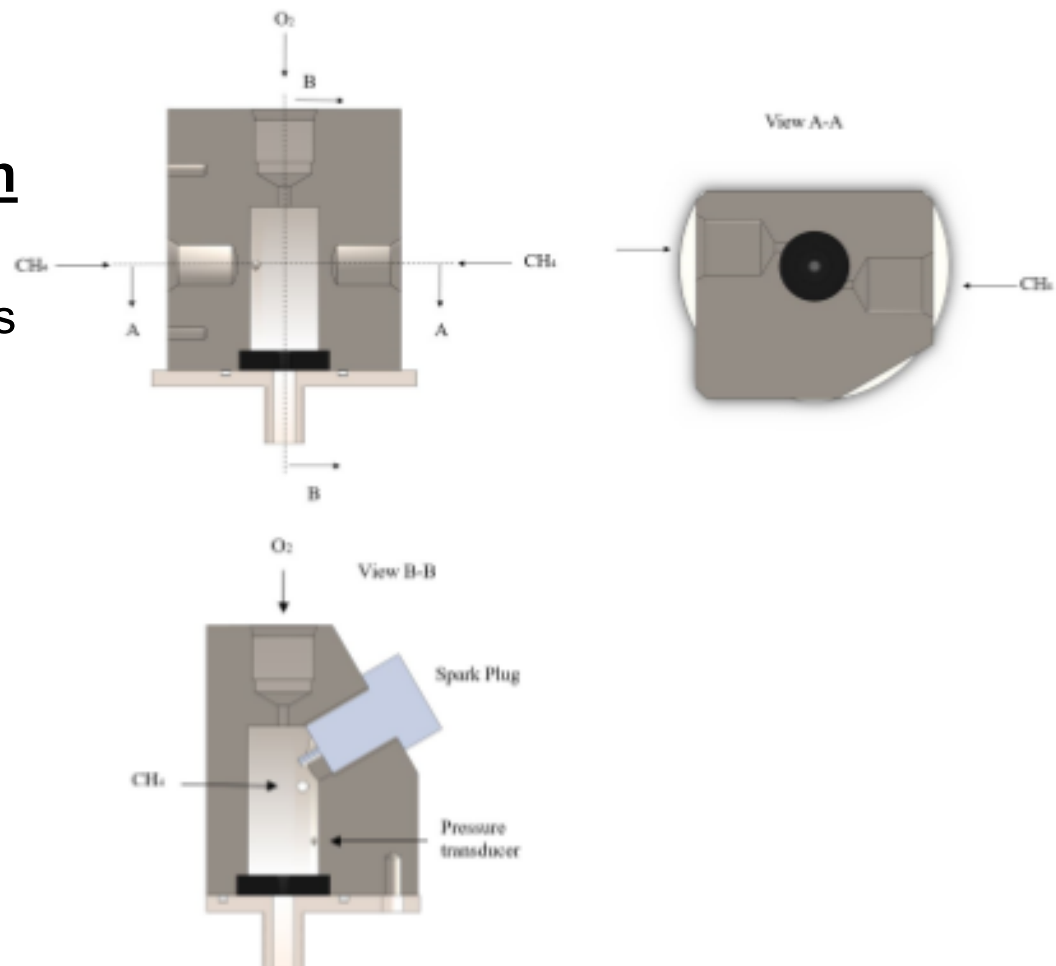
Igniter Design

<u>Spark-Ignition system design</u>

- Chamber diameter: ~0.7 inches
- Chamber length: ~1.4 inches
- Injection Ports
  - 2 methane injectors
  - 1 oxygen injector
- Spark plug Port
- Pressure transducer Port



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Mass Flow Calibration Tests

Test Set Up

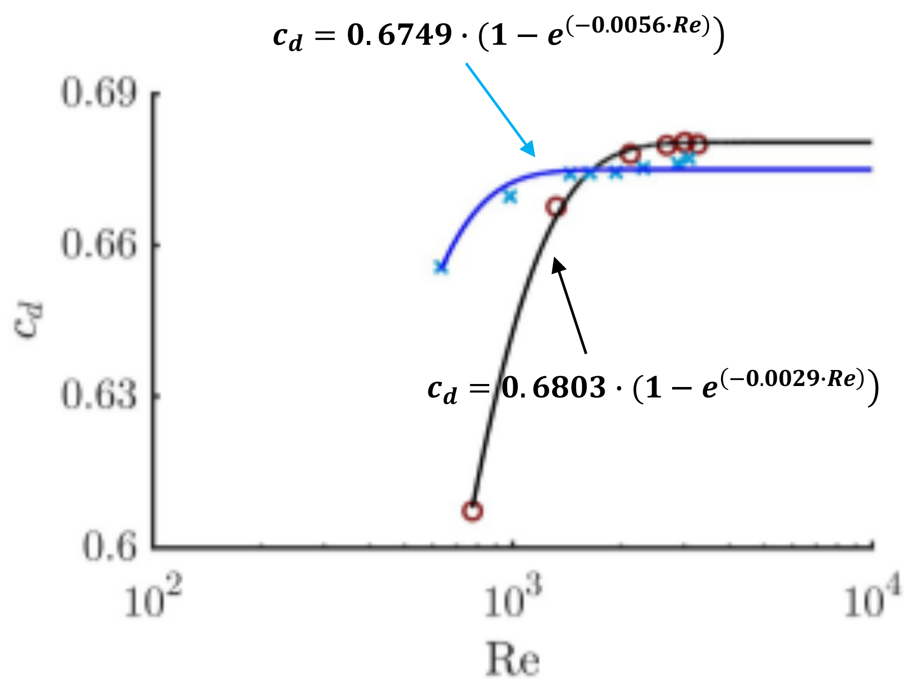
Mass flow rate of oxygen and methane into igniter determined via a pressure transducer and choked orifice

- Orifice discharge coefficient (C_d) determined using nitrogen gas and a flowmeter

Test data post-process

Discharge coefficient determination in oxygen and methane lines

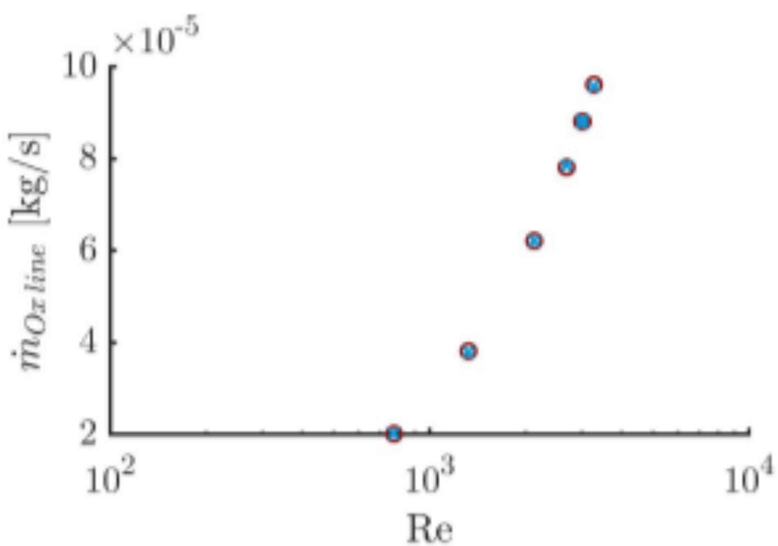
- The logistic function with bounded exponential grow fit experimental data
- Experimental trends in line with the literature

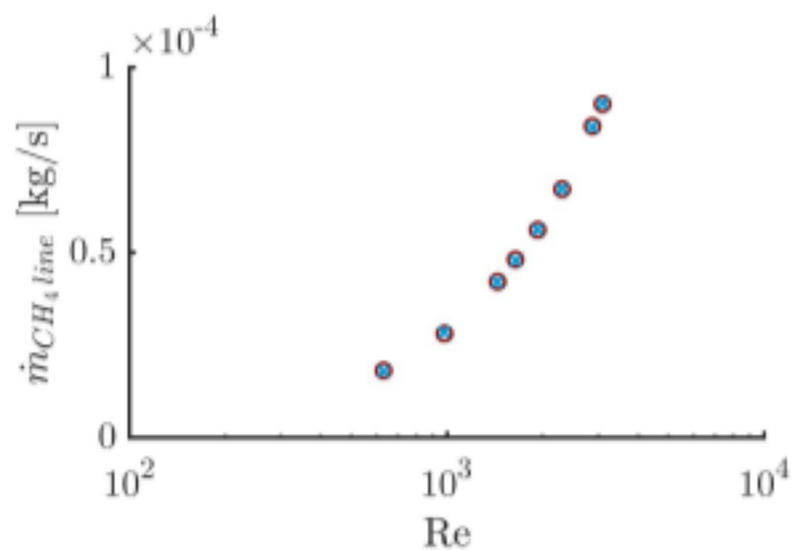


Mass Flow Calibration Tests

Test Results

- A good agreement is seen between mass flow rate calculated with the numerical fit for C_d and the measured mass flow rate values
- The $R_{squared}$ coefficient of the model is 0.9999 for both the oxygen and methane line





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Igniter Tests

A total of 140 igniter tests have been performed to date to characterize the system over a range of different initial conditions and configurations.

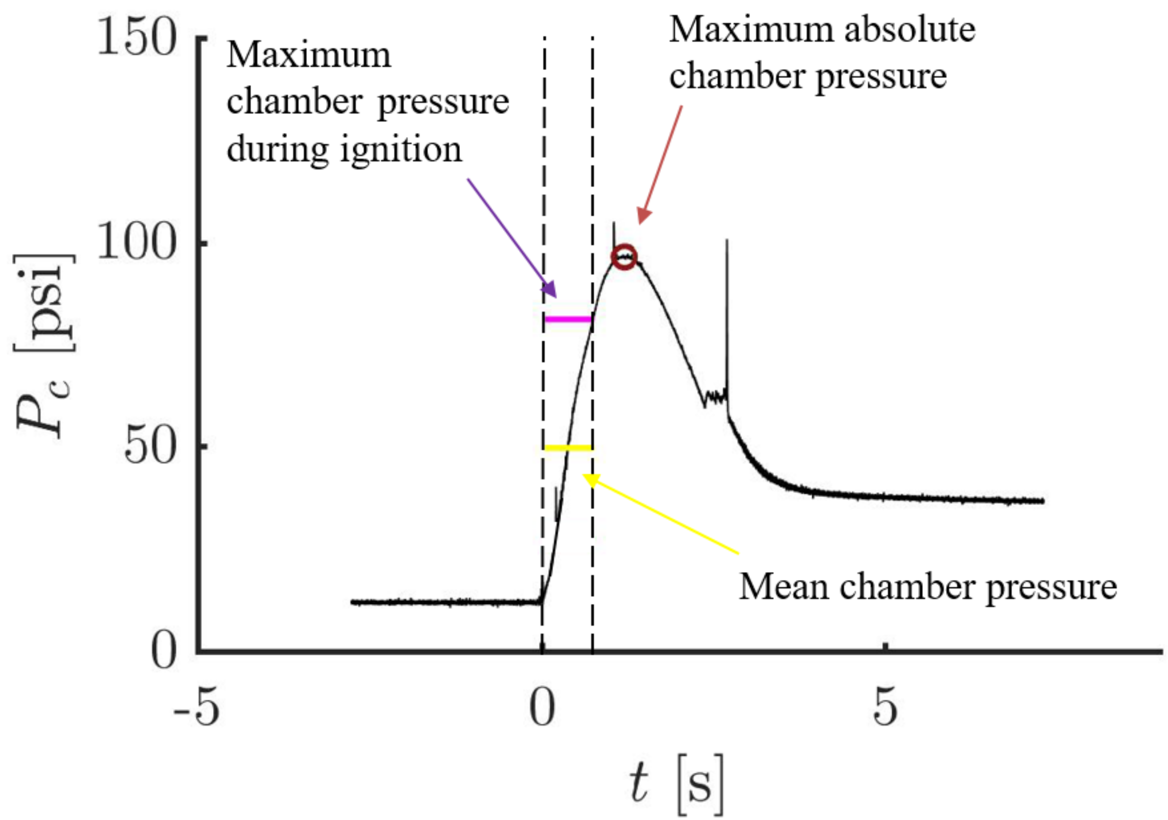
Test Conditions

- Almost constant oxidizer mass flow rate to simulate the baseline flight design (510 psi/ 570 psi)
- Methane flow rate varied to mimic the flight design (50 psi/ 486 psi)
- Igniter chamber pressure: 35 psi/ 105 psi
- O/F ratio range: 2.7 to 31.6 by mass
- Operating test conditions: 5.8% to 43% fuel mole fractions

Igniter Tests

Test Data Post-process

- Actual burn times determined from the pressure traces found to be substantially longer than predicted



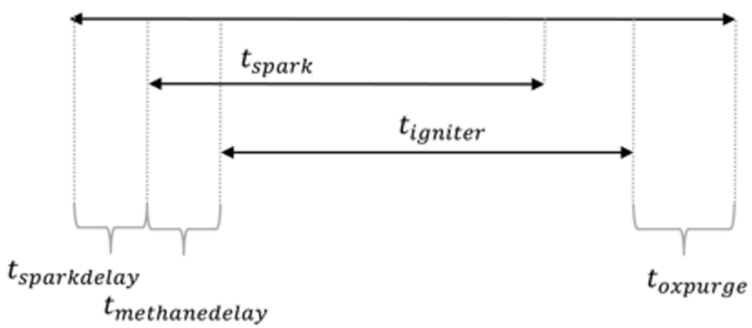
Igniter Tests

Ignition sequence studied in detail to understand the delay.

- Oxygen pressure: 520 psi to simulate the baseline flight design.
- Methane pressure varied, but never dropped below 70 psi to ensure choked flow into the igniter chamber.

Ignition Sequence

$t_{sparkdelay}$: spark plug activation delay
t_{spark}: spark plug activation time
$t_{methanedelay}$: methane injection delay from the spark plug activation time
$t_{igniter}$: time of simultaneous injection of oxygen and methane in the chamber
$t_{oxpurge}$: purge time



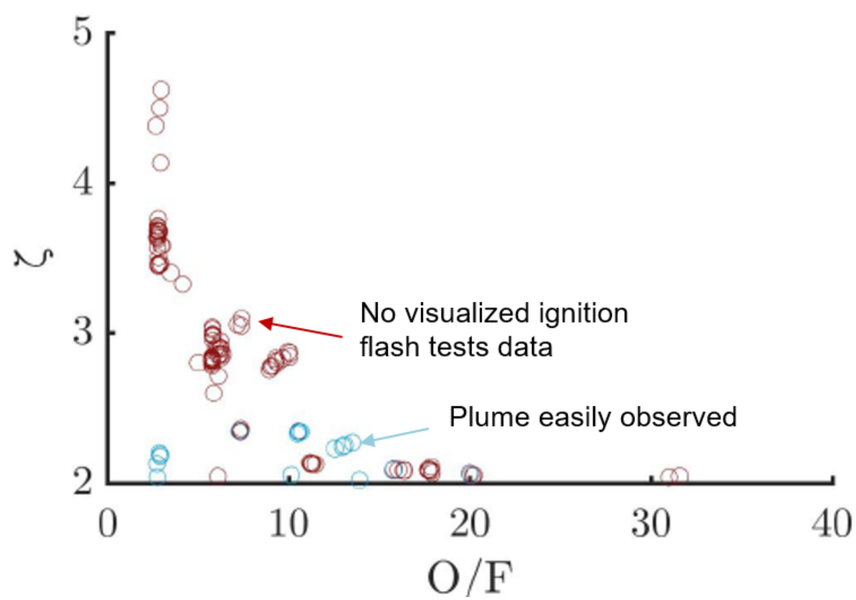
	$t_{sparkdelay}[s]$	$t_{spark}[s]$	$t_{methanedelay}[s]$	$t_{igniteron}[s]$	$t_{oxpurge}[s]$
Nominal	0.05	0.7	0.05	0.7	0.1

Igniter Tests

Successful Ignition Criteria

The ratio between chamber pressure during combustion and the ideal, steady state, chamber pressure during a cold (non-reacting) flow was calculated to understand if combustion was occurring even if it could not be confirmed visually

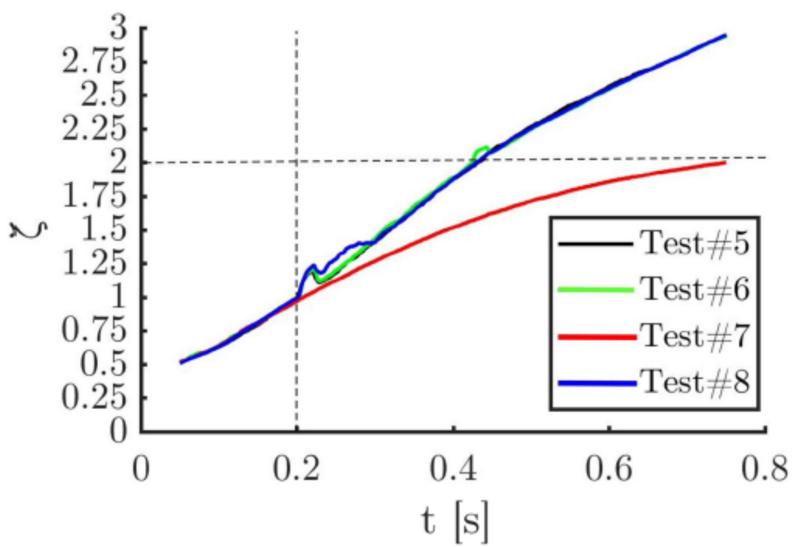
- If ignition occurs, the igniter chamber pressure is expected to rise about this non-reacting steady state pressure value
- Successful ignition defined to occur when the pressure ratio, $\tau = P_c/P_{chamber\ cold}$, is greater than one.



Igniter Tests

Spark Plug On Time Study

	$t_{sparkdelay}[s]$	$t_{spark}[s]$	$t_{methanedelay}[s]$	$t_{igniteron}[s]$	$t_{oxpurge}[s]$
Nominal	0	0.7	0.05	0.7	0.1
Test #5, 03/20/2018	0	0.5	0.05	0.7	0.1
Test #6, 03/20/2018	0	0.7	0.05	0.7	0.1
Test #7, 03/20/2018	0	0.2	0.05	0.7	0.1
Test #8, 03/20/2018	0	0.35	0.05	0.7	0.1



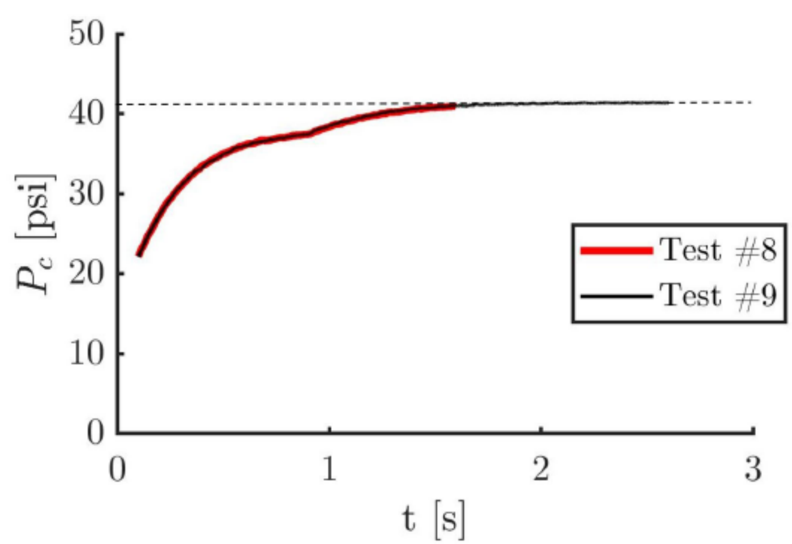
Igniter Tests

Steady State Combustion

	$t_{sparkdelay}[s]$	$t_{spark}[s]$	$t_{methanedelay}[s]$	$t_{igniteron}[s]$	$t_{oxpurge}[s]$
Test #8, 03/15/2018	0.05	0.7	0.05	1.5	0.1
Test #9, 03/15/2018	0.05	0.7	0.05	2.5	0.1

Table 5 C* Efficiency for Steady State Tests.

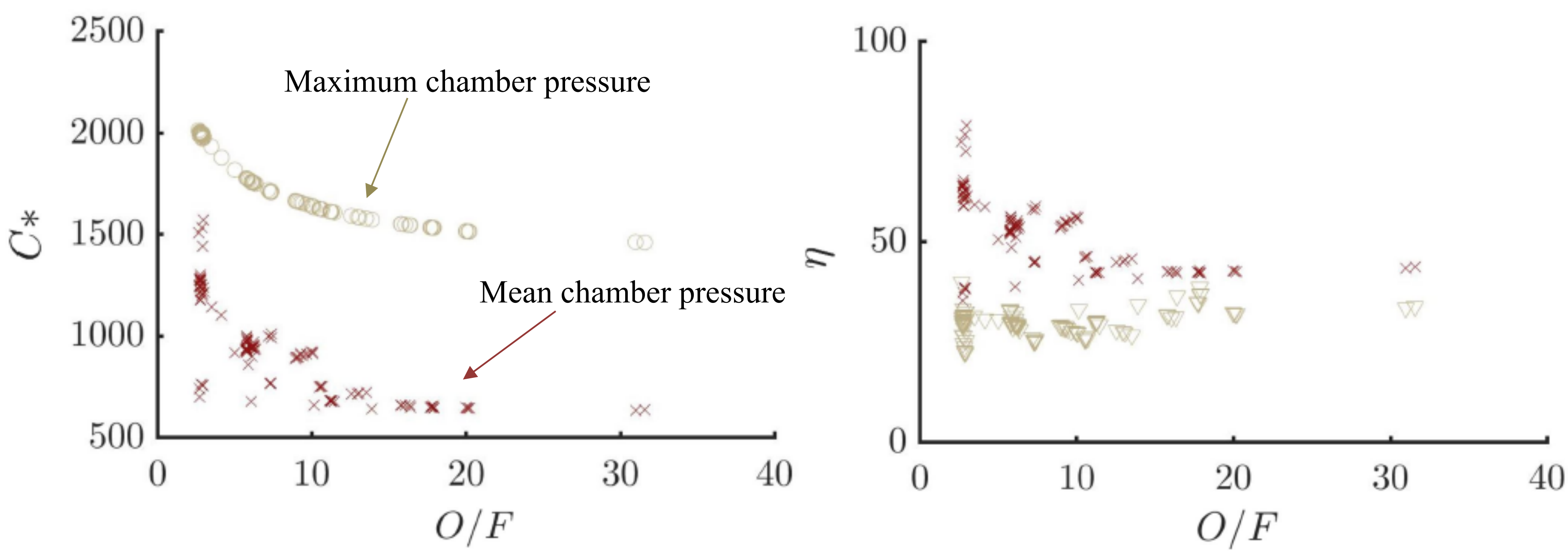
	$t_{igniteron}[s]$	$\frac{\frac{P_{maxabs}A_t}{\dot{m}}}{C^*_{ideal}}$
Nominal	0.7	42.26
Test #8	1.5	44.78
Test #9	2.5	45.33



Igniter Tests

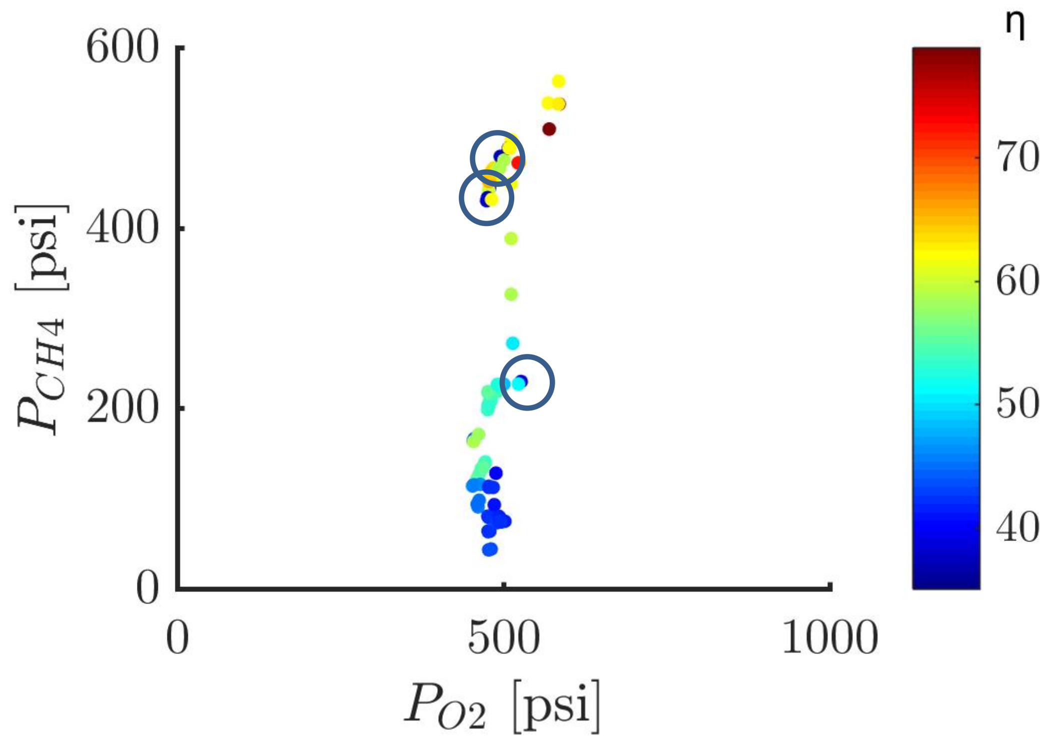
Combustion Efficiency Analysis

$$\eta = \frac{\frac{p_{t_2} A_t}{\dot{m}}}{C^*_{ideal}}$$



Igniter Tests

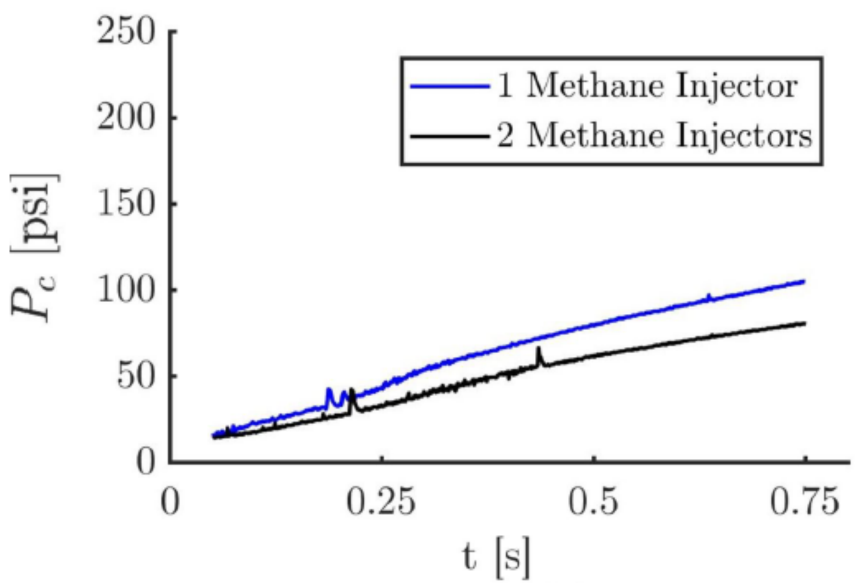
Combustion Efficiency Analysis



Igniter Tests

Igniter tests with one methane injection port

	$t_{sparkdelay}[s]$	$t_{spark}[s]$	$t_{methanedelay}[s]$	$t_{igniteron}[s]$	$t_{oxpurge}[s]$
2 Ch_4 Injectors, Test #5, 03/20/2018	0	0.7	0.05	0.7	0.1
1 Ch_4 Injector, Test #17, 03/20/2018	0	0.7	0.05	0.7	0.1



	Test #	O/F	$\frac{\frac{p_{maxabs}A_t}{\dot{m}}}{C^*_{ideal}}$
2 Ch_4 Injectors	5	2.73	62.03
1 Ch_4 Injector	17	2.68	$\boxed{74.79}$

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Conclusions (1)

Trade Study

- Approximately 140 were conducted to understand the effects of different variables on the ignition performance
- The ignition sequence was studied, to ensure it was repeatable.
- Mechanical valve delays were observed in the pressure trends. These delays were caused by the components selected for this testing and are not representative of a flight motor
- The igniter on times investigated did not allow for steady state combustion to occur in the O_2/CH_4 combustion chamber for short ignition test durations (less than 700 ms)
- To evaluate steady state combustion with the current set up, the injection time of oxygen and methane was increased beyond 700 ms
- One methane injector was adopted instead of two methane injectors and an equivalent test (comparable mass flow rates) was run

Conclusions (2)

Results

- Future testing in a vacuum chamber will use faster-acting solenoid valves to reduce
- Decreasing the O/F shows an increase in efficiency, even beyond ideal stoichiometric conditions. This is likely due increased mixing caused by increased momentum in the tangentially injected fuel when the fuel mass flow rate is increased.
- The C* efficiency is in generally greater than 40% and the maximum value of 78:9% is observed at an O/F = 2.97. It was found to be higher for a test conducted with one methane injector as compared to an equivalent test (comparable mass flow rates) with two methane injectors
- Test results suggest the simpler, single port ignition be adopted for future testing and for flight
- Test data to date shows reliable igniter chamber ignition at a range of O/F, which enables for fuel blow-down in the flight design

Questions?

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